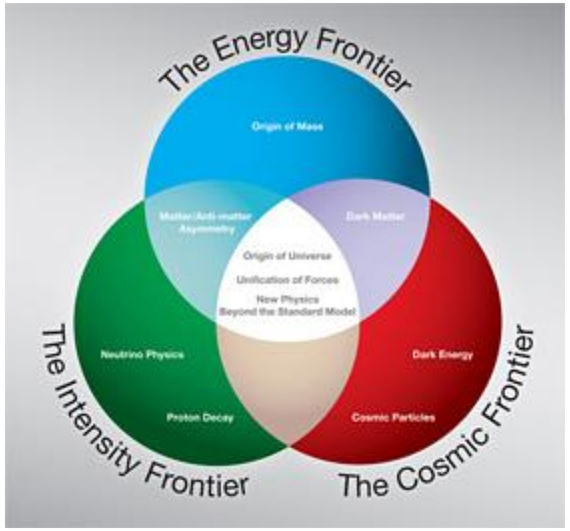
Testing the standard model …. with neutrons

S. Roccia

Outlook

The search for the neutron electric dipole moment

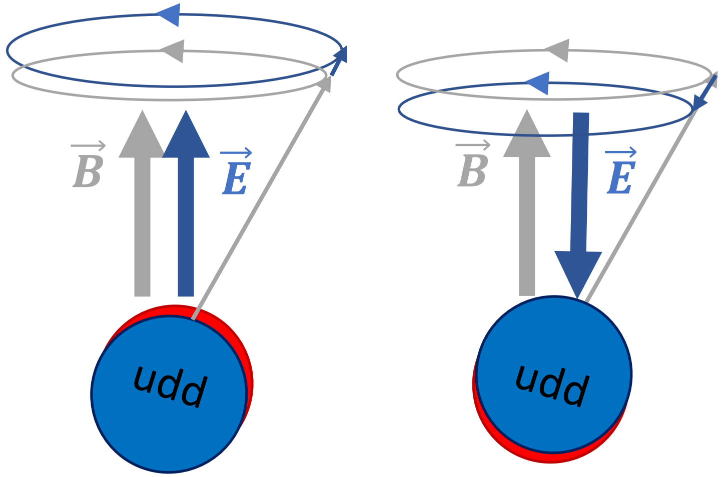
Probing the CKM matrix



What is an EDM?

CP odd!

$$H = -\vec{\mu_n}.\vec{B} - \vec{d_n}.\vec{E} = \frac{h\, f_n}{2}$$



d_n = (0.0 ± 1.1 $_{stat}$ ± 0.2 $_{syst}$) 10^{-26} e.cm

10 years, 34 PhD thesis, 55 persons at a given time

The neutron spin as a quantum clock
- Magnetic field -> 30 turns each second
- Electric field -> 1 turn in 200 days

High precision?
-> we store neutrons for 3 minutes
-> nuclear magnetic resonance
-> atomic magnetometry

CP violation in the standard model: the weak sector

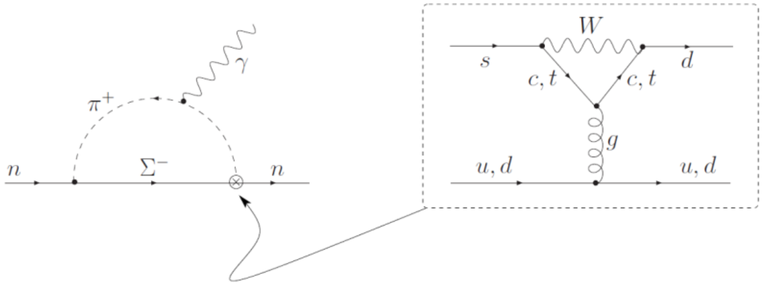
The neutron EDM (from quarks' EDM)

Naive (valence) approach: $d_n = \frac{4}{3}d_d - \frac{1}{3}d_u \leq 10^{-34}\ e.cm$

The neutron EDM (from "long" distance effect)

The largest Standard Model contribution to d_n comes not from quark EDMs, but from a four-quark operator generated by a so-called "strong penguin" diagram. This is enhanced by long distance effects, namely the pion loop, and it has been estimated that this mechanism

$$d_n \approx 10^{-32}\ e.cm$$



The neutron EDM is essentially free of SM background!

Annals of Physics 318 (2005) 119–169

* PRL(2015)062001

The strong CP problem and the axion

$$L_{eff} = L_{QCD} + \theta \, \frac{\alpha_S}{8\,\pi} \, \varepsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

From lattice calculations: $d_n = -0.0039(2)(9)\theta \; e.fm$*

Experimental upper limit: $|d_n| \leq \; 2.10^{-13} \;\; e.fm$

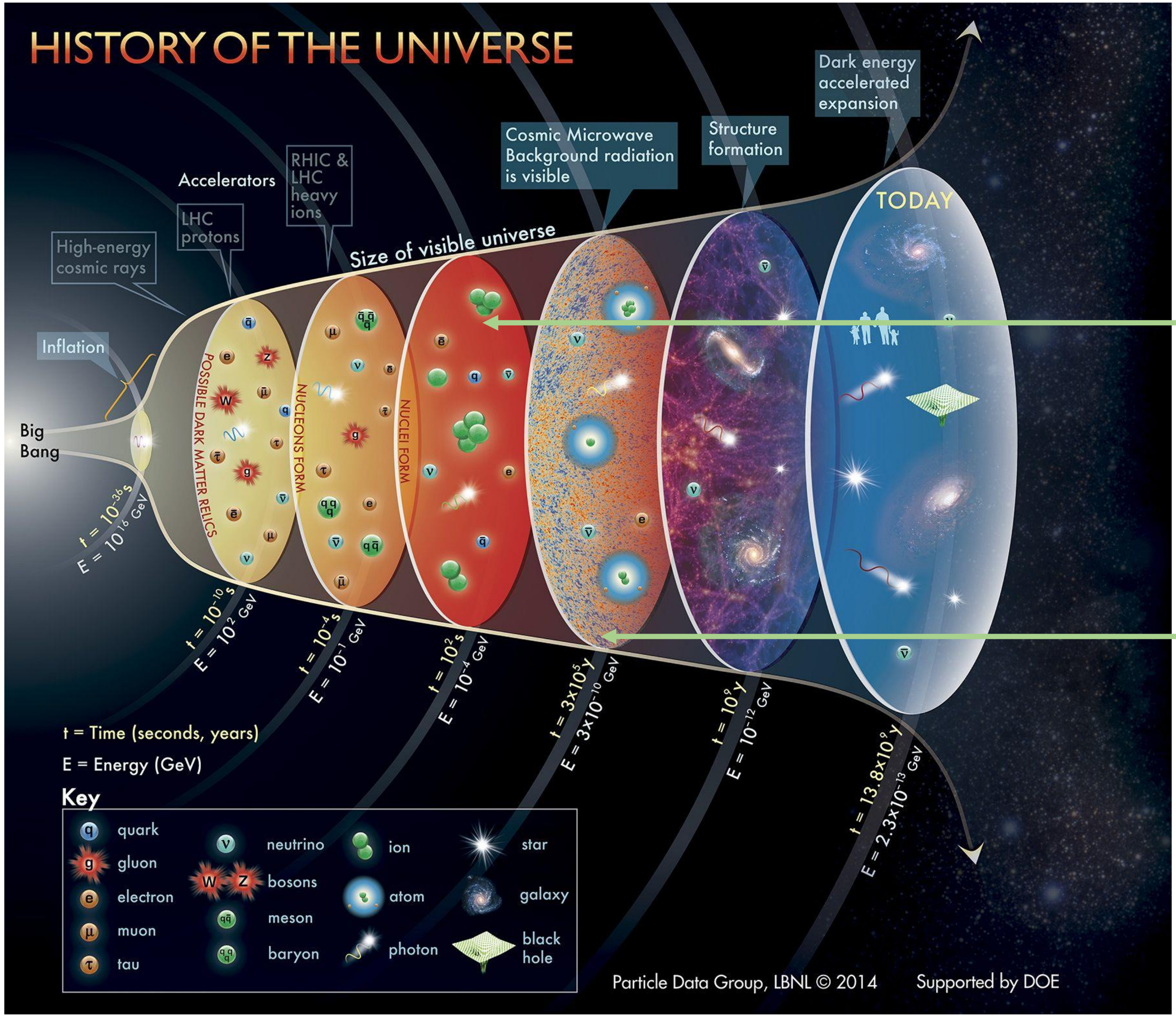
$\theta \leq 10^{-10}$

The strong CP problem

* One mass quark is exactly zero but PDG: $m_u \; = 2.2^{+0.6}_{-0.4} \; MeV$
* Introducing a global chiral U(1) symmetry

This symmetry is necessarily spontaneously broken, and its introduction into the theory effectively replaces the static CP-violating angle θ with a dynamical CP- conserving field- the axion. The axion is the Nambu-Goldstone boson of the broken U(1) symmetry.

Matter/Antimatter Asymmetry of the Universe



$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

The abundances of the light elements depend almost solely on the baryon-to-photon ratio

D/H measurements* + nucleosynthesis models

$$5.8\ 10^{-10} < \eta < 6.6\ 10^{-10}$$

The Planck result**: fraction of cosmological density contained in baryons:

$$\eta = 6.09\ (6)\ 10^{-10}$$

*Universe 3, 44 (2017)

**Astron. & Astrophys. 594, A13 (2016)

Matter/Antimatter Asymmetry of the Universe

How this asymmetry can be explained with particle physics?
→ **Sakharov criteria for baryogenesis**

1) There must exist an interaction that violates B-number.

2) The B-violating interaction must go out of thermal equilibrium.

3) There must be an interaction that violates C & CP.

Standard Model

1) OK (Sphalerons)

2) ~OK (Requires low Higgs mass)

3) Not OK (CKM)

Electroweak baryogenesis

New CP violating phases contributes to

* baryonic asymmetry of the universe
* neutron EDM

$$d_n = d_n^{CKM} + 10^{-16}\, e.cm\, (\theta) + 10^{-24}\, e.cm \left(\frac{200\ GeV}{M}\right)^2 \sin(\varphi_{CP})$$

The nEDM is one of the most stringent test of electroweak baryogenesis

Another possibility is the leptogenesis

Jorinde van de Vis, March 3, 2026

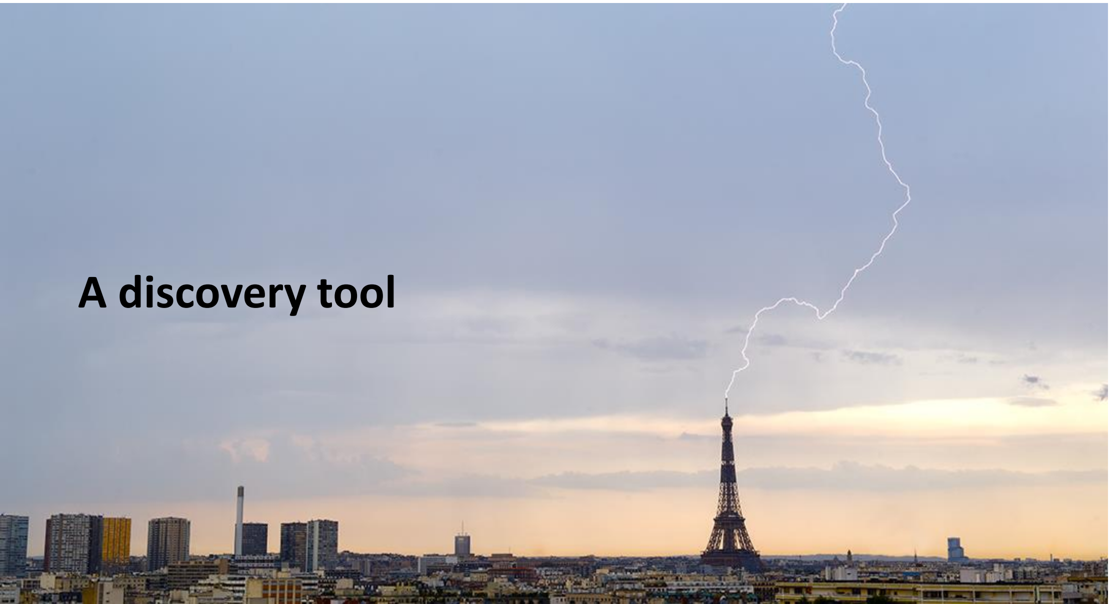
Search for new physics

The chances to find new physics can be quantified in an **effective field theory approach**: the new physics is parameterized by a single energy scale representing the mass of the new force mediators **Λ**, and a large set of dimensionless coefficients

$$\mathscr{L}_{SMEFT} = \sum_{D=2}^{\infty} \sum_{i} O_{i,D} \frac{c_{i,D}}{\Lambda^{D-4}}$$

Wilson coefficients

D is the dimension of the operators $O_{i,D}$
D ≤ 4 describes the Standard Model
D=5 impacts on the neutrino sector
D=6 our playground



At D=6

$$\mathcal{O}_{1\,LR}^{ij\,lm} = \bar{d}^m \gamma^\mu P_L u^l \, \bar{u}^i \gamma_\mu P_R d^j \,, \qquad \mathcal{O}_{2\,LR}^{ij\,lm} = \bar{d}^m_\alpha \gamma^\mu P_L u^l_\beta \, \bar{u}^i_\beta \gamma_\mu P_R d^j_\alpha$$

Nuclear dipoles pick up many contributions from many CP violating operators; even more when RG running is taken into account

$$d_n = \Big((43 \pm 27)\tilde{C}_{1\,LR}^{us\,us} + (210 \pm 130)\,\tilde{C}_{2\,LR}^{us\,us} + (22 \pm 14)\,\tilde{C}_{1\,LR}^{ud\,ud} + (110 \pm 70)\,\tilde{C}_{2\,LR}^{ud\,ud}$$
$$-(0.93 \pm 0.05)\,\tilde{c}_{\gamma u}^{uu} - (4.0 \pm 0.2)\,\tilde{c}_{\gamma d}^{dd} - (0.8 \pm 0.9)\,\tilde{c}_{\gamma d}^{ss}$$
$$-(3.9 \pm 2.0)\,\tilde{c}_{gu}^{uu} - (16.8 \pm 8.4)\,\tilde{c}_{gd}^{dd} \pm (320 \pm 260) v^2 C_{\tilde{G}} \Big) \times 10^{-9}\, e\,\mathrm{fm}\,,$$

$$-\frac{eQ_d}{2} \sum_{ij \in \{d,s,b\}} m_{d_j} C_{\gamma d}^{ij} \bar{d}_L^i \sigma^{\mu\nu} F_{\mu\nu} d_R^j$$

$$-\frac{eQ_u}{2} \sum_{ij \in \{u,c\}} m_{u_j} C_{\gamma u}^{ij} \bar{u}_L^i \sigma^{\mu\nu} F_{\mu\nu} u_R^j$$

$$-\frac{g_s}{2} \sum_{ij \in \{u,c\}} m_{u_j} C_{gu}^{ij} \bar{u}_L^i \sigma^{\mu\nu} G_{\mu\nu}^a t^a u_R^j - \frac{g_s}{2} \sum_{ij \in \{d,s,b\}} m_{d_j} C_{gd}^{ij} \bar{d}_L^i \sigma^{\mu\nu} G_{\mu\nu}^a t^a d_R^j$$

$$C_{\tilde{G}} \frac{g_s}{3} f^{abc} G_{\mu\nu}^a G_{\nu\rho}^b \widetilde{G}_{\rho\mu}^c$$

Alioli et al. 1703.04751

Adam Falkowski, lecture at Les Houches (nEDM2021)

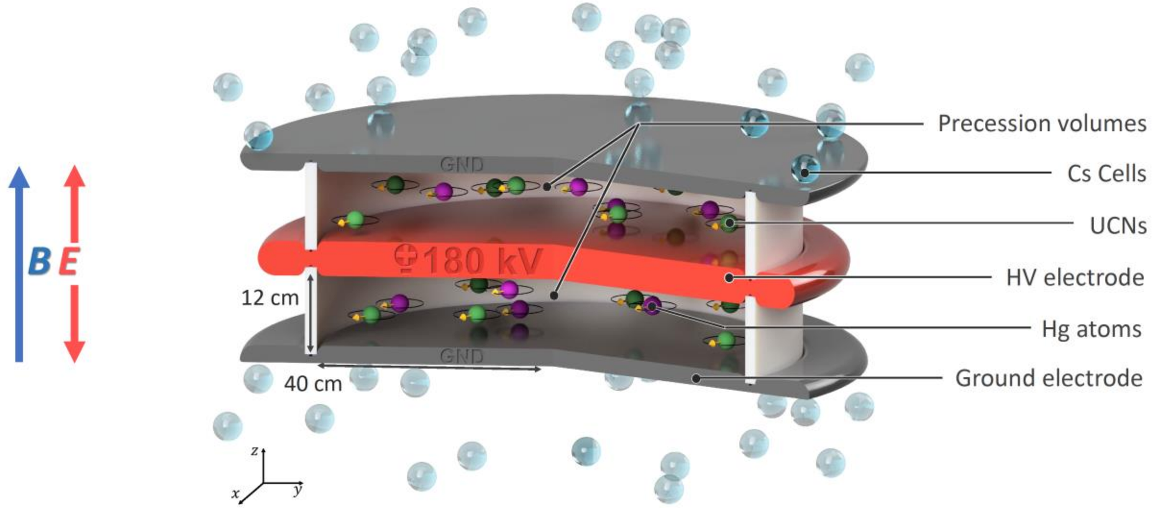
The search for the neutron EDM

First limitation ….. Magnetic field fluctuations

$$\begin{aligned} h\ f_n\ (\uparrow\uparrow) &= 2\ \vec{\mu}_n.\vec{B}(\uparrow\uparrow) + 2\ \vec{d}_n.\vec{E}(\uparrow\uparrow) \\ h\ f_n\ (\uparrow\downarrow) &= 2\ \vec{\mu}_n.\vec{B}(\uparrow\downarrow) - 2\ \vec{d}_n.\vec{E}(\uparrow\downarrow) \\ \hline h(f_n\ (\uparrow\uparrow) - f_n\ (\uparrow\downarrow)) &= 2\vec{\mu}_n.(\vec{B}(\uparrow\uparrow) - \vec{B}(\uparrow\downarrow)) + 2\vec{d}_n.(\vec{E}(\uparrow\uparrow) + \vec{E}(\uparrow\downarrow)) \end{aligned}$$

n2EDM

Goal: 1*10^{-27} e.cm



$$R = \frac{f_n}{f_{Hg}} = \frac{\gamma_n B_n}{\gamma_{Hg} B_{Hg}} = \frac{\gamma_n}{\gamma_{Hg}}$$

The search for the neutron EDM

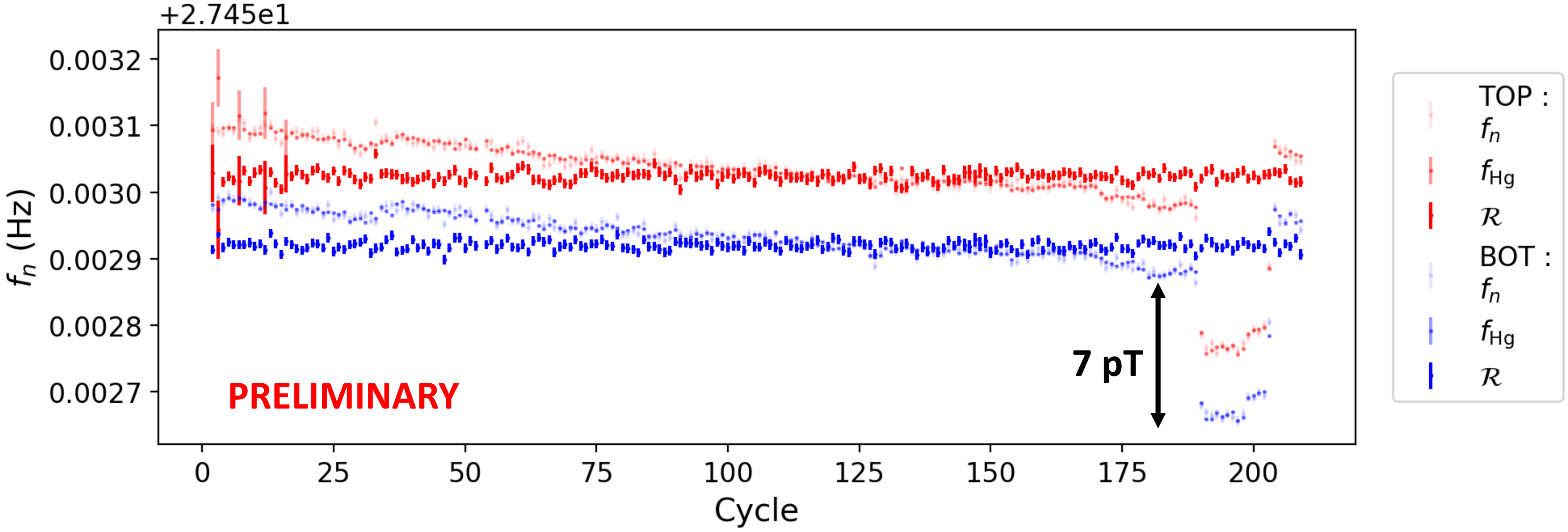
First limitation ….. Magnetic field fluctuations

$$h\ f_n\ (\uparrow\uparrow) = 2\ \vec{\mu}_n.\vec{B}(\uparrow\uparrow) + 2\ \vec{d}_n.\vec{E}(\uparrow\uparrow)$$

$$h\ f_n\ (\uparrow\downarrow) = 2\ \vec{\mu}_n.\vec{B}(\uparrow\downarrow) - 2\ \vec{d}_n.\vec{E}(\uparrow\downarrow)$$

$$h(f_n\ (\uparrow\uparrow) - f_n\ (\uparrow\downarrow)) = 2\vec{\mu}_n.(\vec{B}(\uparrow\uparrow) - \vec{B}(\uparrow\downarrow)) + 2\vec{d}_n.(\vec{E}(\uparrow\uparrow) + \vec{E}(\uparrow\downarrow))$$

K. Michielsen & M. Ferry



Data taking in progress

Beta decay as a laboratory for testing the weak interaction

A long history

- Observation of « beta rays » could be the very beginning of particle physics?
- Parity violation observed in 1957

… many crucial ingredients of the Standard (electroweak) Model

And today?

Universality of the weak interaction, the equality of the Fermi constant as felt by leptons and quarks, is one of the cornerstones of SM -> **the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix**

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} = 1$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

Beta decay as a laboratory for testing the weak interaction

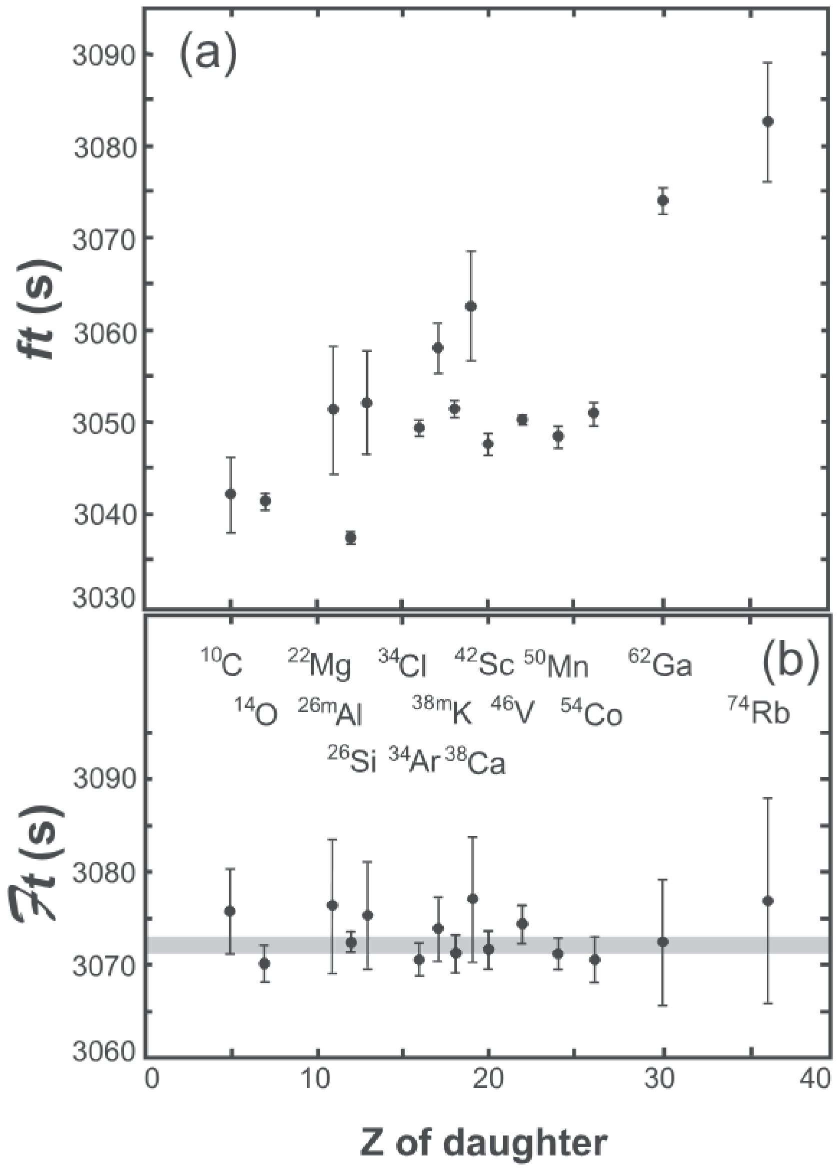
$0^+ \rightarrow 0^+$ "superallowed" beta decay

$$\mathcal{F}t = \frac{K}{2V_{ud}^2 G_F^2 (1 + \Delta_R^V)}$$

Radiative correction

$$\mathcal{F}t = ft(1 + \delta'_{\mathrm{R}})(1 + \delta_{\mathrm{NS}} - \delta_{\mathrm{C}})$$

Nuclei dependant



PHYSICAL REVIEW C 102, 045501 (2020)

Beta decay as a laboratory for testing the weak interaction

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$$\mathcal{F}t = \frac{K}{2V_{ud}^2 G_F^2 (1 + \Delta_R^V)}$$

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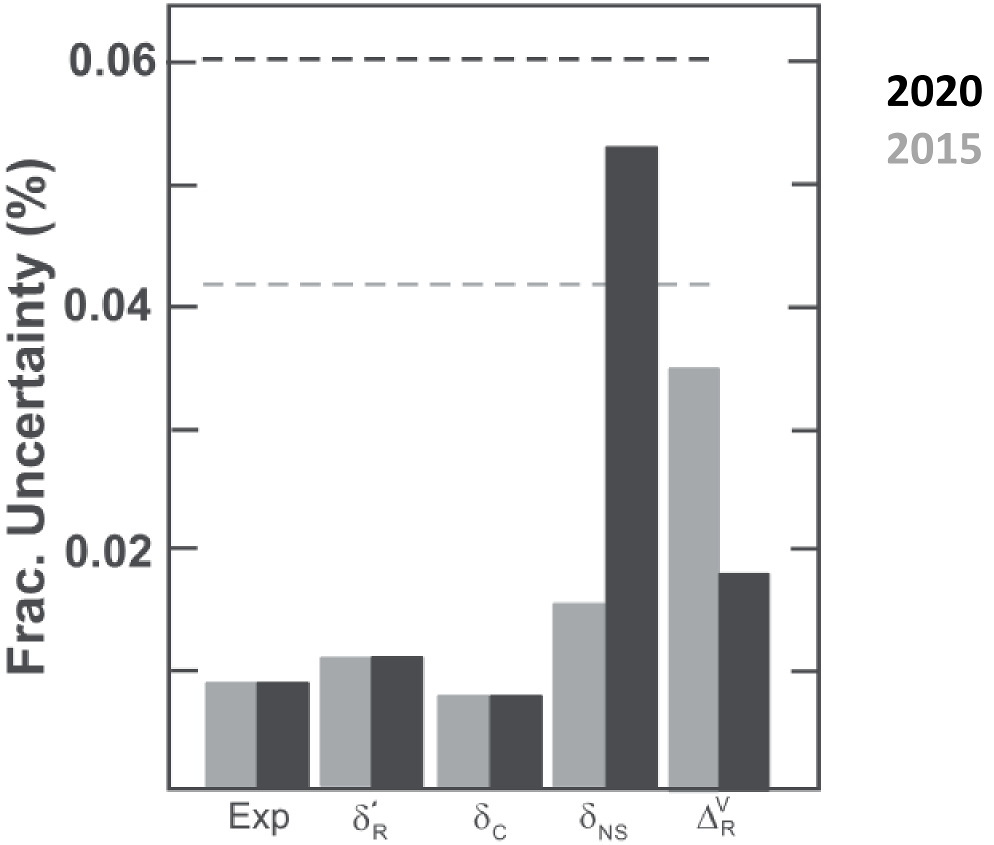
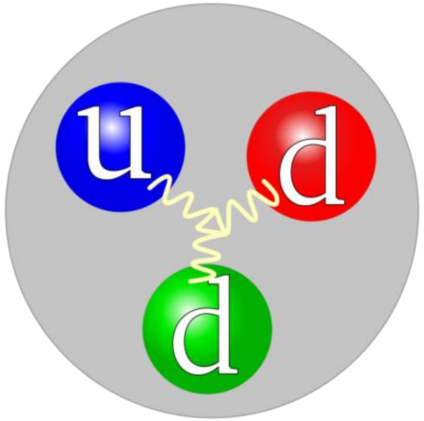


$$|V_{ud}| = 0.97373 \pm 0.00031$$

Increased error bars!

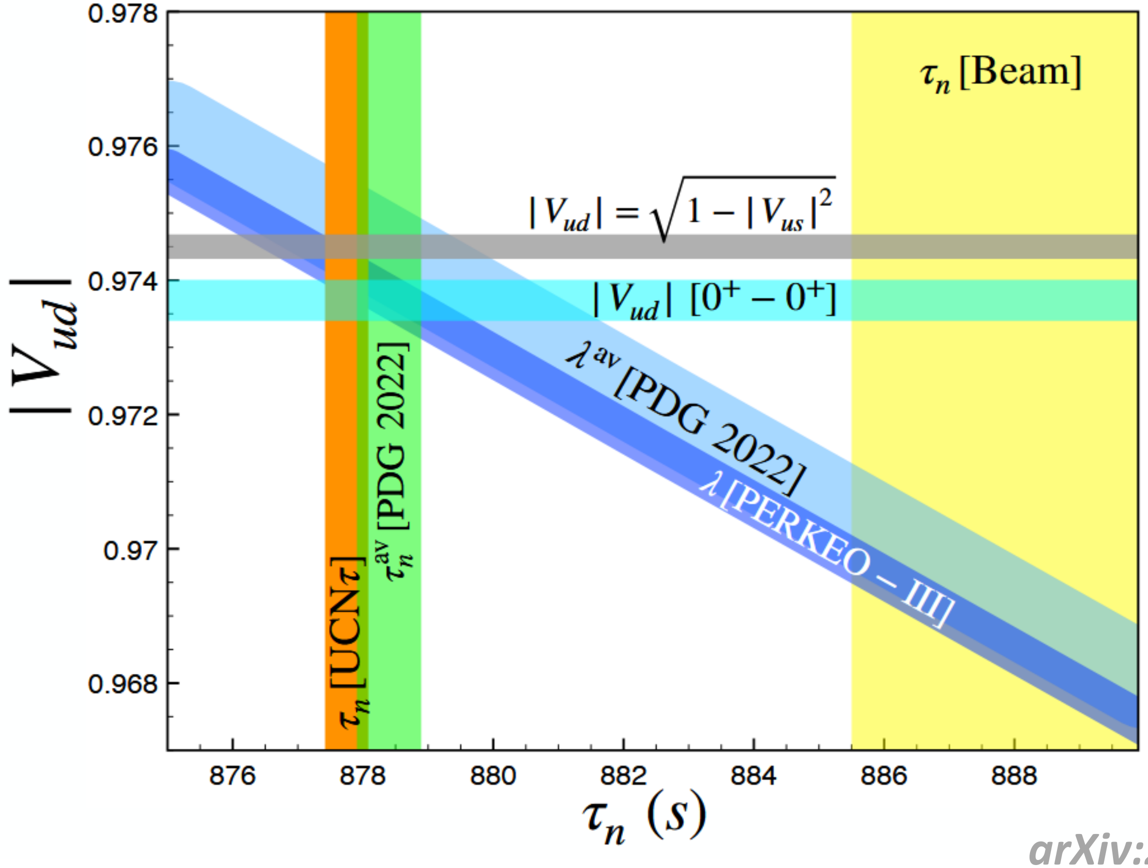
PHYSICAL REVIEW C 102, 045501 (2020)

Beta decay as a laboratory for testing the weak interaction



Here comes the neutron!

$$|V_{ud}|^2_n \propto \frac{1}{\tau_n(1+3\lambda^2)}$$



Ratio of the axial-vector and vector coupling constants

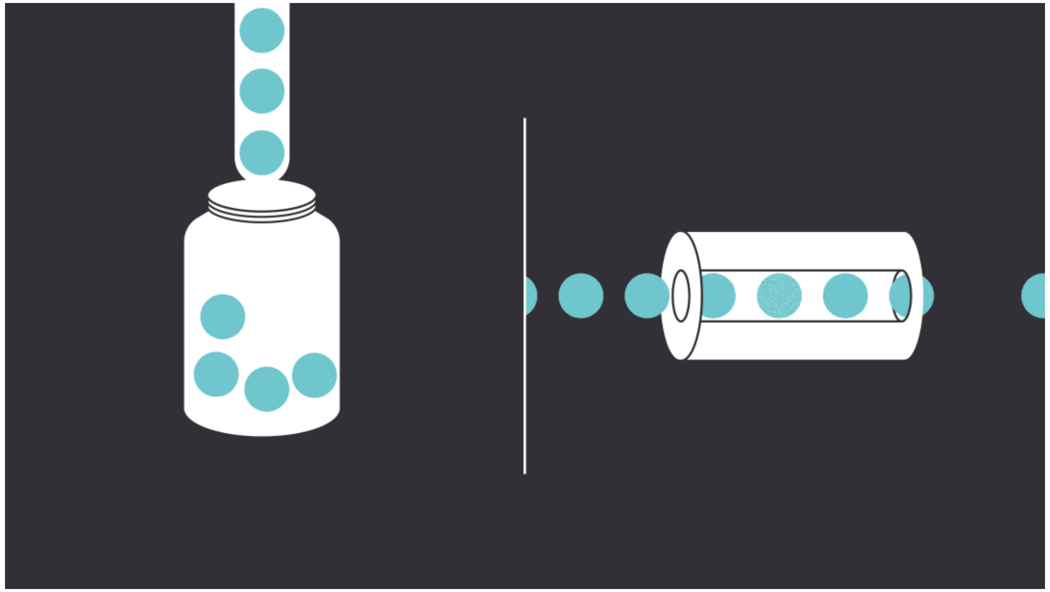
$$\lambda = g_A/g_V$$

arXiv:2307.01145v3

Beta decay as a laboratory for testing the weak interaction

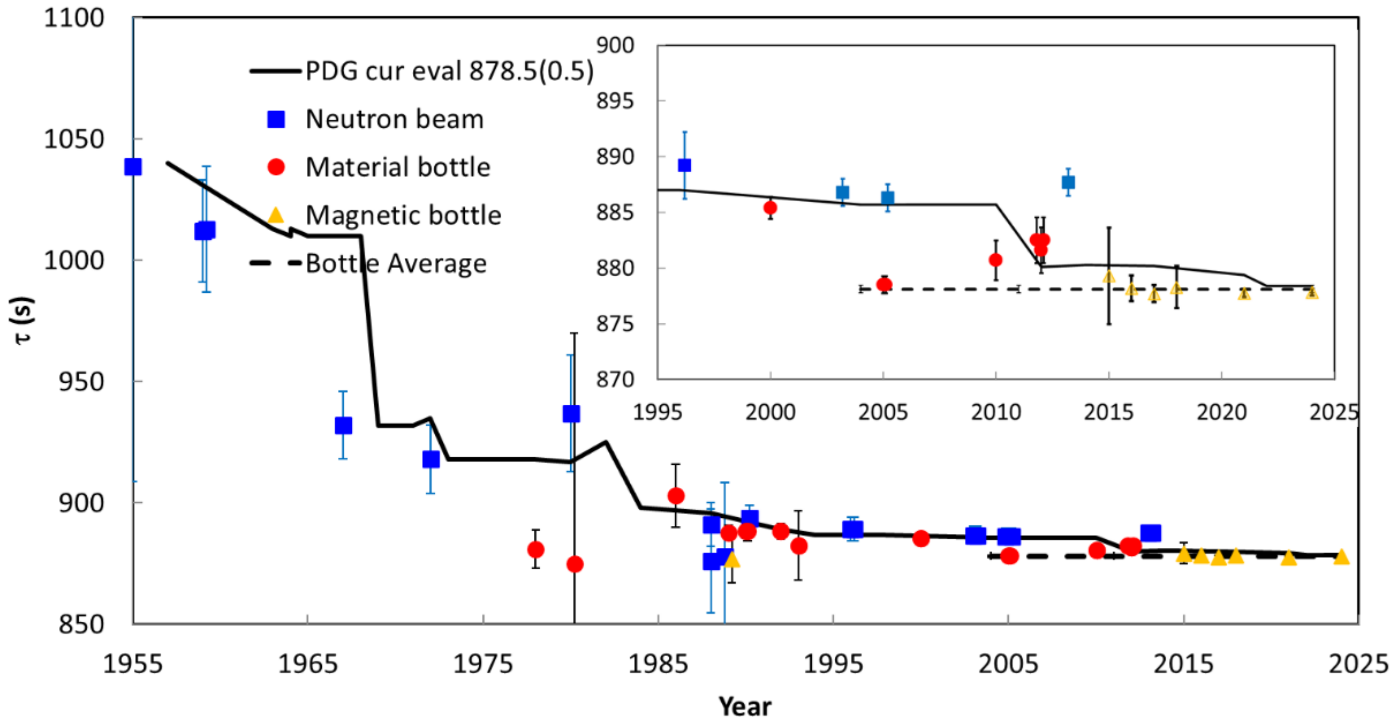
A dark side of the neutron?

Storage:
Counting the
living ones



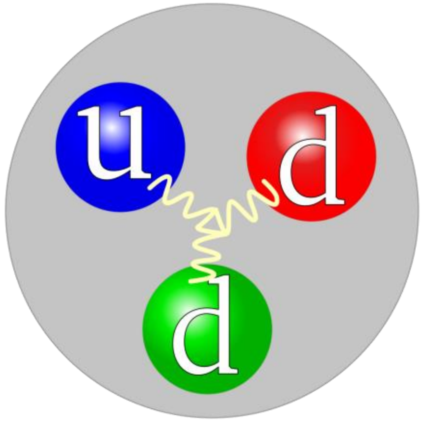
Beam:
Counting the
dead ones

Beta decay as a laboratory for testing the weak interaction



877.82±0.22 (statistical)+0.20-0.17 (systematic) s

Beta decay as a laboratory for testing the weak interaction



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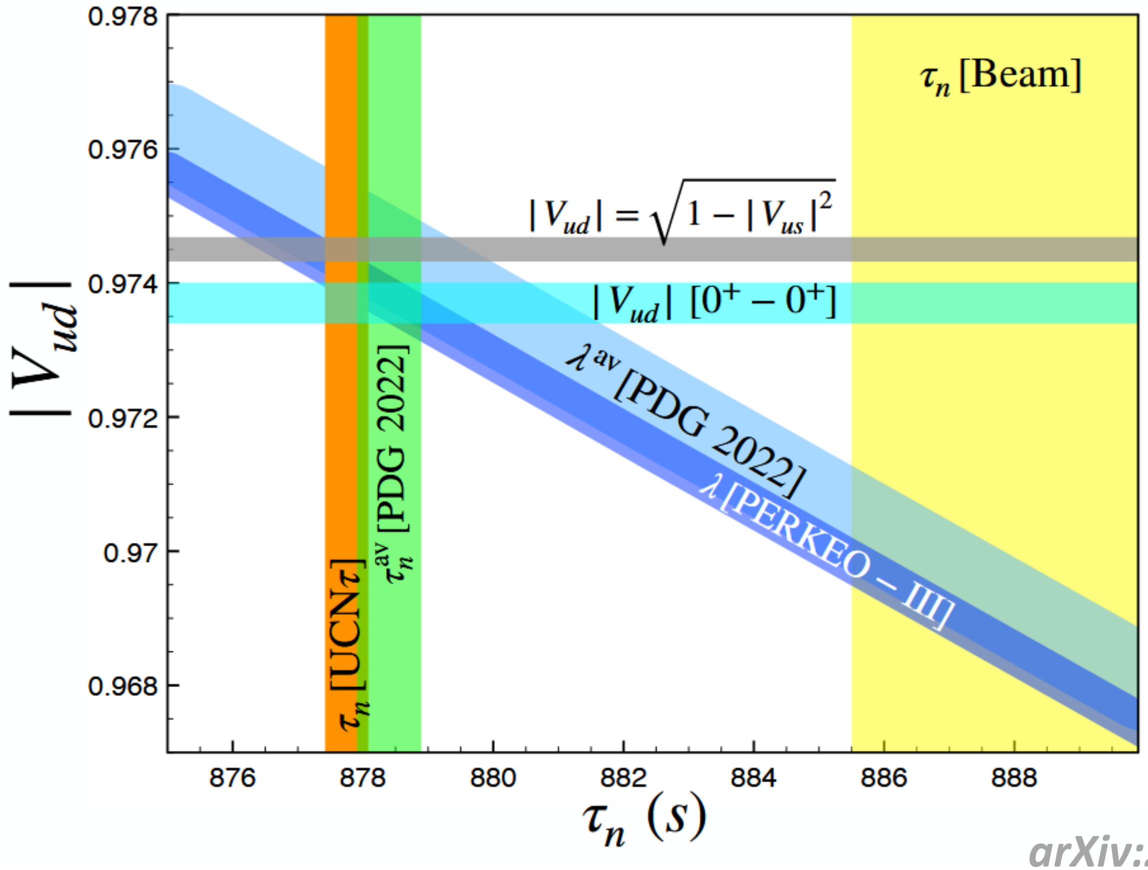
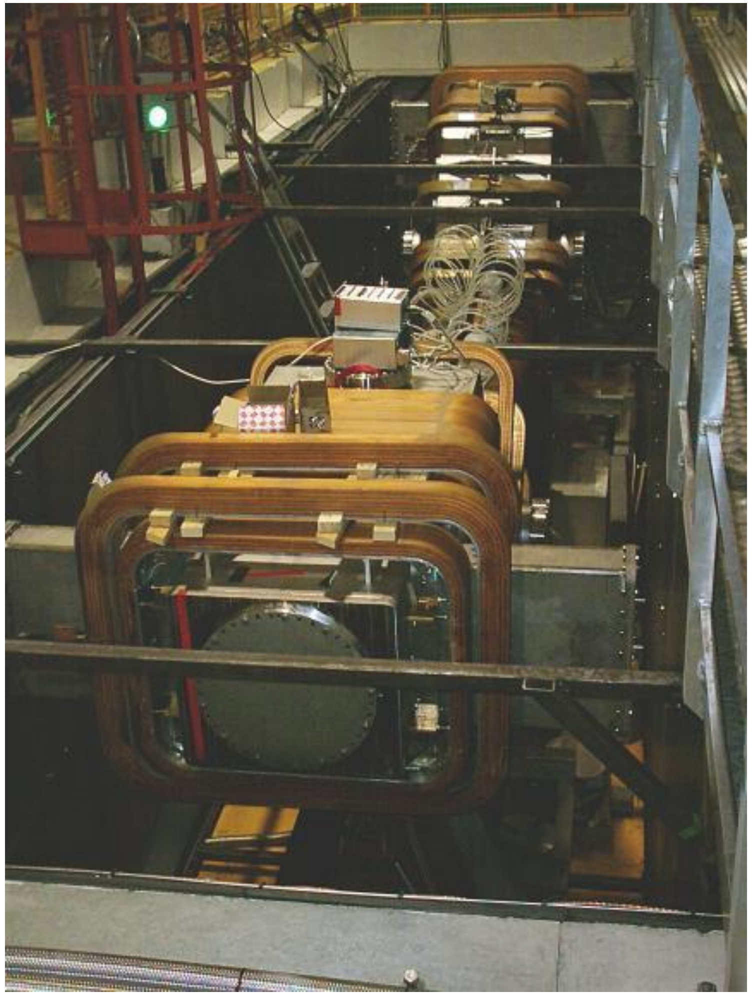


arXiv:2307.01145v3

Beta decay as a laboratory for testing the weak interaction

PERKEO III @PF1b



PHYSICAL REVIEW LETTERS **122**, 242501 (2019)

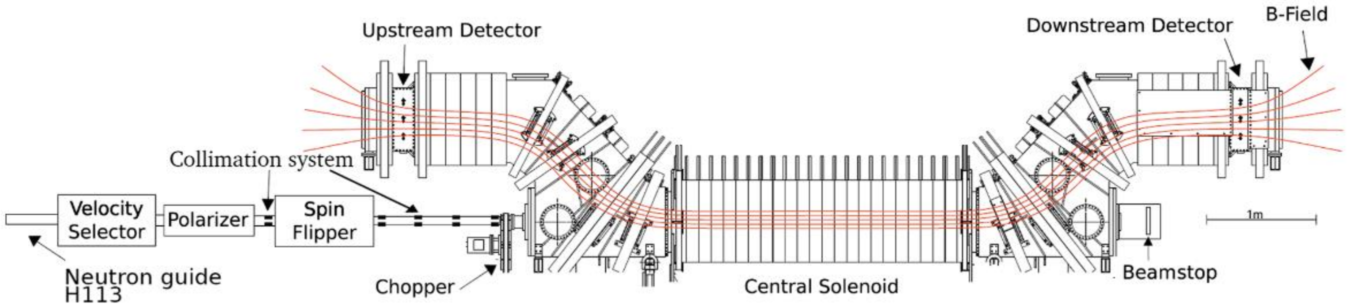


FIG. 1. Schematic of the spectrometer setup PERKEO III installed at PF1B. The magnetic field is indicated in red. The cold neutron beam from the reactor source enters the beam line on the left-hand side. Picture from [35].

Electron velocity

$$W(\vartheta) = 1 + \frac{v}{c} P A \cos\vartheta$$

Angle of the electron emission with respect to the neutron spin

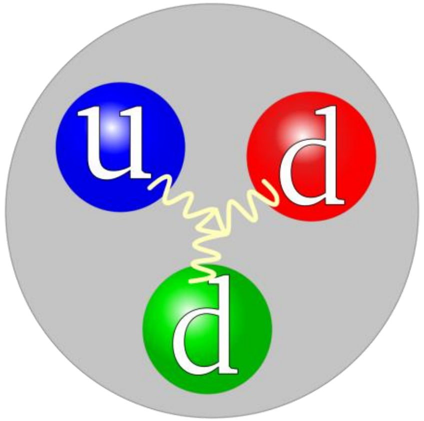
Neutron polarisation

$$A_0 = -2\frac{\lambda(\lambda+1)}{1+3\lambda^2}$$

Ratio of the axial-vector and vector coupling constants

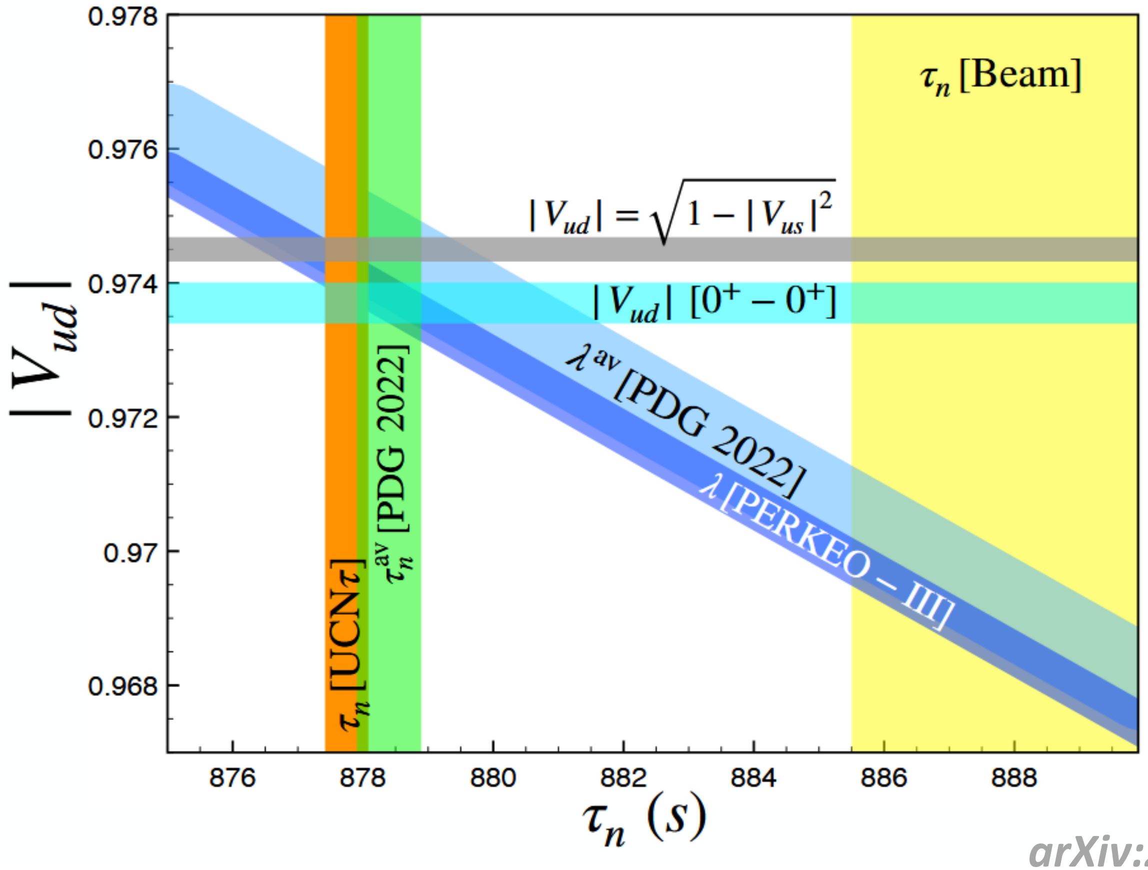
$$\lambda = g_A/g_V = -1.27641(45)_{\text{stat}}(33)_{\text{sys}}$$

Beta decay as a laboratory for testing the weak interaction



Here comes the neutron!

$$|V_{ud}|_n^2 \propto \frac{1}{\tau_n(1+3\lambda^2)}$$



Neutron only

$$V_{ud} = 0.97408(11)_{RC}(28)_{\tau}(32)_{\lambda} = 0.97408(44)$$

0+ → 0+

$$V_{ud} = 0.97373(31)$$

arXiv:2307.01145v3

Neutron is the best particle

Fundamental Nuclear and Particle Physics At Neutron Sources

Submitted by all participants of and contributors to the Fundamental Nuclear and Particle Physics at the ESS workshop, held January 15—17, 2025 at Lund University as input to the European Strategy for Particle Physics Update

H. Abele[8], J. Amaral[55], W.R. Anthony[1], L. Åstrand[2], M. Atzori Corona[57], S. Baeßler[1,11], M. Bartis[3], E.Baussan[4], D. H. Beck[5], J. Bijnens[6], K. Bodek[7], J. Bosina[8], E. Bossio[9], G. Brooijmans[10], L. J. Broussard[11], G. Brunetti[12], A. Burgman[13], M. Cadeddu[14], N. Cargioli[14], J. Cederkall[2], A. Chambon[15], T. W. Choi[16], P. Christiansen[2], V. Cianciolo[11], C. B. Crawford[17], S. Degenkolb[18], N. Delarosa[3], M. Demarteau[11], K. Dickerson[19], D. D. DiJulio[3], F. Dordei[14], Y. Efremenko[11,20], T. Ekelöf[16], M. Eshraqi[3], R.R. Fan[21], M. Fertl[22], H. Filter-Pieler[23], B. Fornal[24], G. Fragneto[3], C. Gatto[25,26], P. Geltenbort[23], F. Ghazi Moradi[3], H. Gisbert[27], P. Golubev[2], M. González-Alonso[28], G. Gorini[12]

P. Heil[29], N. Hermansson-Truedsson[2,30], Y. Hiçyılmaz[31], M. Holl[2], T. Ito[32], K. E. Iversen[2], T. Jenke[23], M. Jentschel[23], M. Juni Ferreira[33], S. Kawasaki[48], E. Kemp[56], P. Kinhult[3], M. Kitaguchi[34], J. Klenke[35], W. Korten[36], A. Kozela[24], B. Lauss[37], M. Lebert[35], W. Lee[3], T. Lesiak[24], C.-Y. Liu[5], L. Löbell[38], A. Longhin[39], E. Lytken[2], B. Märkisch[38], J. Marton[8], B. Meirose[2,40], N. Milas[3], D Milstead[13]

F. Monrabal[41], S. Moretti[16,42], P. Mueller[11], A. Nepomuceno[43], J. Newby[11], R. Nieuwenhuis[2], T. Palasz[44], R. Pasechnik[2], S. Penttila[11], M. Persoz[29], L. B. Persson[2], F.M. Piegsa[29], B. Plaster[17], I. Pradler[8], F. Pupilli[39], K. Pysz[24], T. Quirino[55], J. C. Ramsey[11], B. Rataj[2], J. Rathsman[2], S. Roccia[45], D. Rozpedzik[44], D. Rudolph[2], E. Salehi[3], V. Santoro[2,3], A. Saunders[11], H. Shimizu[34], H. Schober[3,46], K. Scholberg[47],

W. Schreyer[11], A. Schubert[38], D. Silvermyr[2], O. Smirnova[2], W.M. Snow[49], T. Soldner[23], S.R. Soleti[41], Y. V. Stadnik[50], R. Strauss[38], F. Terranova[12], T. Tolba[51], N. Tsapatsaris[3], L. Vale Silva[52], W. Van Goethem[16], R. Wagner[53], M. Wolke[16], W. Yao[11], N. Yazdandoost[37], A.R. Young[54], L. Zanini[3], M. Zielinski[7]

arXiv:2506.22682

Axion detour

The axion is a well motivated dark matter candidate

Axion density relative to the critical density of the universe

$$\Omega_a \approx \left(\frac{6\,\mu\text{eV}}{m_a}\right)^{\frac{7}{6}} \approx \Omega_m = 0.23\ (m_a \approx 20\ \mu eV)$$

Entire dark matter density

The theory is quite predictive

Essentially all of the physics of the axion depends on a large unknown energy scale f_a, at which Peccei-Quinn symmetry is broken.

The axion has a two photons coupling, and g_γ is model dependant.

$$m_a \approx 6\,\text{eV}\left(\frac{10^6\,\text{GeV}}{f_a}\right)$$

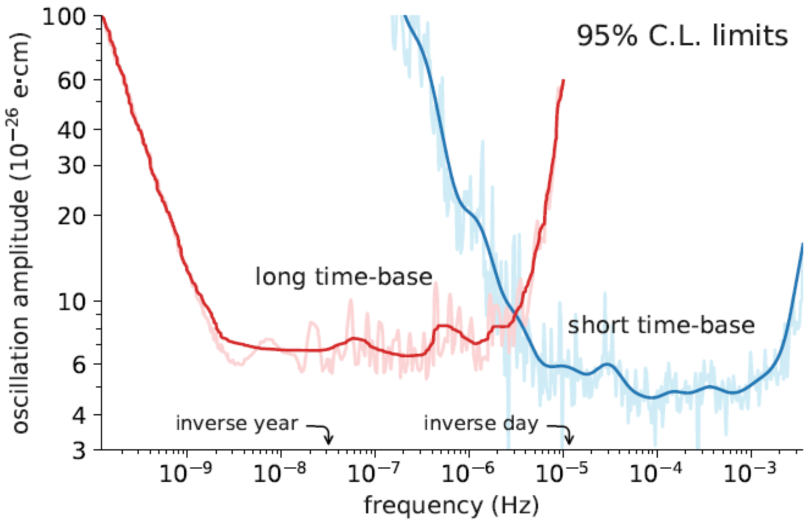
$$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a}$$

Search for Axion-like dark matter

Search for the interactions of the **coherently oscillating axion** DM field with gluons and fermions
-> oscillating electric dipole moments (EDMs) of nucleons
-> anomalous spin-precession effects

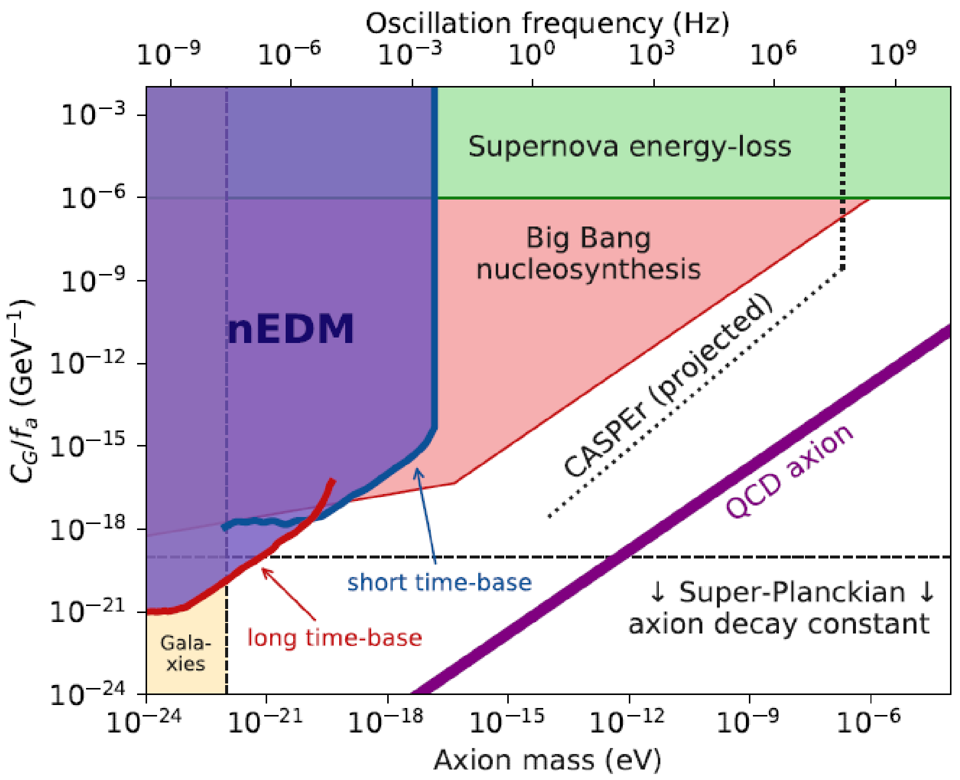
$$a = a_0 \cos(\omega t)$$
$$\omega \approx m_a c^2/\hbar$$

$$d_{\mathrm{n}}(t) \approx +2.4 \times 10^{-16} \, \frac{C_G a_0}{f_a} \cos(m_a t) \; e \cdot \mathrm{cm} \, .$$



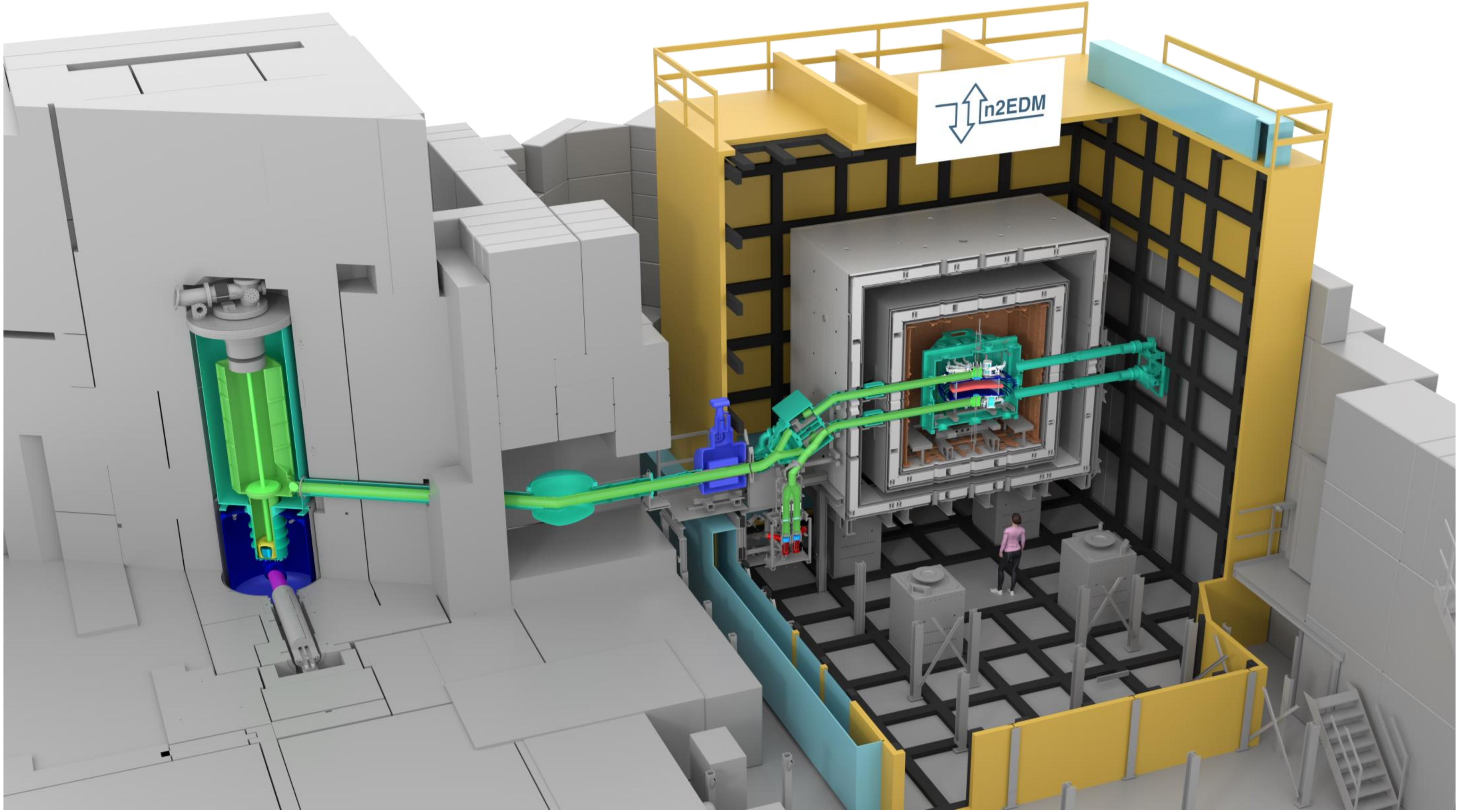
ILL data: long data taking

PSI data: high sensitivity
Still blinded

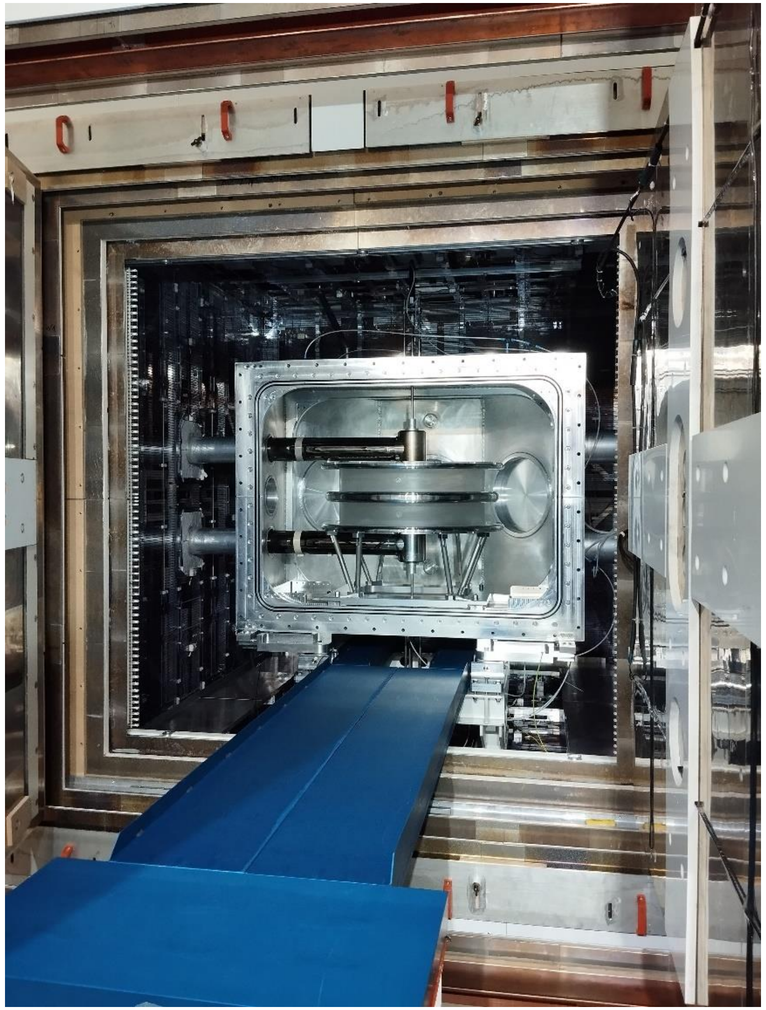


C. Abel et al., Phys. Rev. X 7, 041034 (2017)

The search for the neutron EDM



The search for the neutron EDM



n2EDM